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Neural correlates of the number–size interference task in children

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Abstract

In this functional magnetic resonance imaging study, 17 children were asked to make numerical and physical magnitude classifications while ignoring the other stimulus dimension (number–size interference task). Digit pairs were either incongruent (3 8) or neutral (3 8). Generally, numerical magnitude interferes with font size (congruity effect). Moreover, relative to numerically adjacent digits far ones yield quicker responses (distance effect). Behaviourally, robust distance and congruity effects were observed in both tasks. imaging baselline contrasts revealed activations in frontal, parietal, occipital and cerebellar areas bilaterally. Different from results usually reported for adultssmaller distances activated frontal, but not (intra-)parietal areas in children. Congruity effects became significant only in physical comparisons. Thus, even with comparable behavioural performance, cerebral activation patterns may differ substantially between children and adults.

Keywords

anterior cingulate cortex; cerebellum; congruity effect; developmental functional magnetic resonance zimaging study; distance effect; dorsolateral prefrontal cortex; intraparietal sulcus; number–size interference task

Introduction

The ability to compare two numerals (5>3) is a fundamental numerical skill. Distant numerals (3 and 8) are easier to compare than close numerals (3 and 4), which is referred to as the distance effect [1]. This has been interpreted as evidence that the internal semantic representations of distant numbers do not overlap and hence do not impose any interference in accessing/retrieving the required response [2]. Furthermore, the distance effect is thought to reflect the integrity of the ‘mental number line’ [3].

Font-size differences have been observed to influence the numerical comparison of two digits. Participants are faster to compare congruent (3 8) or neutral (3 8) digit pairs relative to incongruent (3 8) stimuli [4]. Additionally, numerical magnitude has been observed to influence font size comparisons. This is referred to as the number–size interference effect.

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The interference is assumed to stem from the influence of a task-irrelevant – but automatically processed – stimulus property or dimension [5].

Recent studies investigated the neural correlates of a number–size interference task in adults [6,7] and revealed two major findings: (a) relative to larger distances smaller ones activated bilaterally (intra)parietal areas (distance effect); (b) incongruent trials activated fronto-parietal areas bilaterally, including the precuneus, the anterior cingulate cortex and the dorsolateral prefrontal cortex. Similar frontoparietal activations have been reported in nonnumerical interference tasks (adults: [8]; children: [9]). Prefrontal areas have been found to play a key role in attentional and magnitude processing (for an overview, see [10]).

The present study is the first to investigate the cerebral correlates of the number–size interference task in children. The main aim of the study is to extend our previous findings [6] to the developing brain by subjecting the paediatric group studied here to the same stimuli and testing procedure as reported previously in adults. A recent functional magnetic resonance imaging study assessing age-dependent changes in computational skills found a linear correlation between age and (intra)parietal activation that was not accompanied by a parietal increase in grey matter density [11]. The authors observed in their sample of 8–19-year-old participants that, with increasing age and learning experience, prefrontal activations subserving attentional and working memory demands seem to be less activated when solving simple calculations.

In our group of 8–12-year-old children, we expect robust behavioural distance and congruity effects for the number–size interference task employed here. We expect an activation pattern for the children that would be different from that of the adults [6]. Specifically, we hypothesize that in children the distance effect should yield stronger activations in prefrontal areas (reflecting increased attentional and working memory task demands), but less prominent parietal activations. For the congruity effect, we hypothesize that – similar to adults [6,7] – significant activations should be found in frontal regions including the anterior cingulate cortex and the dorsolateral prefrontal cortex, although they might be less prominent for children than for adults [12].

Materials and methods

Seventeen healthy children participated in this study (mean age 9.6, 10 boys). The children were all right-handed and had average intellectual abilities (mean prorated intelligence quotient according to four subtests of the German version of the Wechsler Intelligence Scale for Children, 3rd revision [13], 113.15/SD 6.66). Moreover, the presence of behavioural/psychiatric impairments was excluded (German version of the Child Behavioural Checklist [14]). The children and their parents had given their written informed consent. The research project was approved by the ethical committee of the Innsbruck Medical University.

The number–size congruity task required two types of magnitude judgements on a pair of single digits: in the physical task, children had to indicate the physically larger digit, while ignoring numerical magnitude. In the numerical task, they had to indicate the numerically larger digit, while ignoring physical size. Two numerical distances (distance 1: 2–3, 3–4, 6–7, 7–8 and distance 4: 2–6, 3–7, 4–8) and two physical distances (font sizes for distance 1: 55–64, 64–73, for distance 2: 55–73 in Arial) were used. The small numerical distance was always combined with a large font size difference. The large numerical distance was always combined with a small physical distance. Depending on the tasks, this combination yields maximal interference (small distance for the relevant stimulus property; large distance for the irrelevant stimulus property) or minimal interference (vice versa). The experiment consisted of these two tasks; order of task presentation was counterbalanced. Stimuli were presented in activation blocks consisting of six trials each alternating with fixation (30 s). In total, 2(task)× 4(condition)× 12(stimuli per condition)=96 stimuli were presented in 16 blocks. An interstimulus interval of 3000 ms (stimulus presentation 2000 ms, blank screen 1000 ms) was chosen to be asynchronous with the interscan interval of 2.7 s. Stimuli were presented by using Presentation (http://nbs.neuro-bs.com/). Children were instructed carefully and had completed a training session outside the scanner. During scanning, children had to press one of two buttons according to the location of the (numerically or physically) larger number of the digit pair. Instructions emphasized accuracy and speed.

Functional magnetic resonance images were acquired with a 1.5 T whole-body system (Magnetom VISION, Siemens, Erlangen, Germany). For the functional measurement, an echoplanar imaging sequence was used (TR/TE/α=0.96 ms/66 ms/90°, matrix=64 × 64, voxel dimension=3.91 × 3.91 × 6.25 mm^3, 24 axial slices). A deflatable vacuum cushion minimized head movement. A structural image was also acquired (T1, MPRAGE, 0.98 × 0.98 × 1.4 mm^3).

Data analysis was performed using SPM2 software (Wellcome Department of Cognitive Neurology, London, UK). *Preprocessing*: The data were motion corrected. The anatomical image of each child was coregistered to the functional image time series and normalized to the medium age children templates from the Imaging Research Center at Cincinnati Children's Hospital Medical Center [15]. The functional images were normalized using the normalization parameters of the structural image and smoothed with a Gaussian kernel of 8 mm full width at half-maximum. *Statistics:* The block onsets for the different conditions were convolved with the canonical form of the haemodynamic response function as implemented in SPM2. Motion parameters were entered into the analysis as covariates of no interest. The data were high-pass filtered (1/500 Hz). Owing to technical problems (response recording failure in three cases) and our response criterion (<30% error), the final analysis was restricted to 10 (physical comparison) and 12 data sets (numerical comparison). A fixed effects model was estimated over all runs. The resultant statistical parameter maps were thresholded at an uncorrected *P*-value of $P<0.005$ (voxel level). Activations are reported as significant at a *P*-value of <0.05, corrected on a cluster level.

Results

Behavioural results

Children with an error rate greater than 30% in any condition were excluded from further analysis. In the remaining data sets, 69 errors occurred in total, 49 (8.5%) in the numerical comparison and 20 (4.2%) in the physical comparison task. Mean reaction times were computed from correct trials only (Table 1), and trials with reaction times smaller than 300 ms and longer than 4000 ms were discarded. Significant distance effects (DEs: neutral close>neutral far) and congruity effects (CEs: maximum incongruent>minimum incongruent) were observed in numerical comparison [DEs: $t(11)=5.42$, $P>0.001$; CEs: $t(11)=3.03$, $P<0.05$] and physical comparison [DEs: $t(9)=3.70$, $P>0.02$; CEs: $t(9)=4.92$, $P>0.001$].

Brain imaging results

Baseline contrasts—Comparing activation blocks with fixation revealed distributed bilateral activations in the frontal, parietal, occipital and cerebellar regions bilaterally in both tasks. In both tasks, activations extended to the intraparietal sulcus, the supramarginal gyrus and the cingulate gyrus bilaterally. In the physical comparison task, there were also significant activations in the precentral gyrus bilaterally and in the left thalamus. In the

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numerical comparison task, additional activations were observed in the right superior temporal gyrus, the left angular gyrus and the left lingual gyrus.

Distance effects—In both tasks, close distance trials – relative to far ones – yielded significant activations in middle and inferior frontal brain regions (including the dorsolateral prefrontal cortex) on the right. In the numerical comparison task, significant blood oxygenation level-dependent responses extended to the left anterior cingulate and the superior frontal gyrus bilaterally. Though not significantly activated, parietal regions are not silent upon processing distance in magnitude judgements (Fig. 1).

Congruity effects—No activations became significant in the numerical comparison task. In the physical comparison task, incongruent trials – relative to neutral ones – yielded significant left-sided activations in the inferior and middle frontal regions (extending to the dorsolateral prefrontal cortex), in the inferior and medial occipital regions (including the lingual gyrus) and in the posterior lobe of the cerebellum [16] (Table 2).

Discussion

In this study, we investigated the processing of distance and congruity using a number–size interference task with 8–12-year-old children. Specifically, we aimed at extending previous findings in adults [6] to children. Being confronted with a trade-off between power (block-design) and strategy (event-related), we decided to deviate from the adult study protocol by using a block-design – rather than an event-related – approach in children. The rationale for this decision is two-fold: (a) cerebral activations in children are more distributed (attention [12], inhibition [9], computational skills [11]), which stresses the necessity to use a block-design approach in children as this is more powerful; (b) relative to adults children might be less likely to develop (within one activation block) a problem-solving strategy facilitating answer retrieval. A further technical reason why it is not feasible to directly compare children's and adult's imaging data are that optimal normalization is achieved only if appropriate reference data are used. Hence, we employed paediatric templates in this study, making a direct statistical comparison between children's and adults' data difficult [15]. Overall, we believe that the deviations from the study protocol used in adults [6] are justified and that, because of the identical stimulus materials and scanning parameters, qualitative comparisons of the activation patterns are still valid.

Similar to adults, children showed significant distance and congruity effects in both tasks, with regard to the behavioural data.

The imaging baseline contrasts reveal the well-known fronto-parietal processing network of distance and congruity. Both numerical and physical comparison tasks yielded activations in the frontal, parietal, occipital and cerebellar areas bilaterally. In both tasks, parietal activations were observed in the intraparietal sulcus and the supramarginal gyrus bilaterally. In the numerical task, these activations extended to the left angular gyrus. Parietal activations have often been observed in number-processing tasks [3,6,7,17]. Specifically, the intraparietal sulcus has been associated with magnitude processing [3] and approximate calculation [18]. The angular gyrus and, to a lesser extent, the supramarginal gyrus have been suggested to support the retrieval of number facts [17]. The activation of the angular gyrus in the numerical task might reflect the retrieval of information pertaining to the number symbols, while this is not required in the physical task. Some debate, however, exists about the number specificity of the functions of the angular gyrus and the intraparietal sulcus [6,17,19]. Finally, a novel finding concerns the significant bilateral cerebellar activations in both tasks. Considering the extensive anatomo-functional connections between the cerebellum and prefrontal areas [20] and the complex cognitive requirements of the number–size interference task, two domains of possible hypotheses can be raised. First, the cerebellum might subserve task-specific processing requirements, as a link between the cerebellum and task complexity/novelty has been repeatedly proposed [17,20,21]. Second, the cerebellar activations might be elicited by domain-specific (i.e. numerical) processing requirements (for a more detailed account, see [10]).

Significant activations for distance and congruity effects in fronto-parietal areas are well documented in adults, but not in children. *Distance effects:* in both tasks, the right dorsolateral prefrontal cortex was significantly activated, while the left anterior cingulate cortex was significantly activated only in the numerical task. Different from the pattern observed with adults [6], we did not observe significant activations in (intra)parietal brain areas. Nonetheless, parietal regions are not completely silent in children upon processing distance (Fig. 1). Interindividual differences might be masked by group-wise data analysis and it is possible that in single children parietal regions are involved in magnitude processing. Likewise, the functional maturation of this region might be delayed, with less diffuse and more focal patterns of activity in the mature system (as demonstrated previously with regard to attention [12] and inhibition [9]). Our failure to find robust (intra)parietal activations in response to numerical distance in children is also compatible with a recent developmental study on computational skills [11]. The stronger frontal involvement in magnitude classification tasks in children as compared with that in adults might reflect the higher attentional task demands or more effortful semantic processing [11,12]. Overall, despite comparable behavioural distance effects in both comparison types for children and adults, imaging results differ for children and adults.

Congruity effects did not become significant in the numerical task. This is unexpected as font size – which is the interfering stimulus dimension in this task – is a very salient stimulus feature [2]. In the physical task, activation foci were found in the cerebellar as well as (pre)frontal and occipital (including the lingual gyrus) areas on the left. Prefrontal activations in response to interference processing may reflect the recruitment of attentional and working memory resources [21]. Reports of cerebellar activations upon interference processing are scarce and most plausibly explained by task complexity/novelty [11,20]. The finding of occipital activations in incongruent trials is surprising, given the visual similarity between incongruent and neutral trials. The fusiform and the lingual gyrus have been associated with letter and visual word form analysis [21]. It is possible that the higher attentional demands in the incongruent condition modulated the activation in visual processing areas.

Conclusion

The most important finding of this study is that – even in case of comparable behavioural performance patterns – cerebral activation patterns need not be identical in children and adults. Contrary to our previous findings on adults, the numerical distance effect did not yield significant (intra)-parietal activations in children. Finally, our study is the first to report significant cerebellar activations in a number–size interference task.

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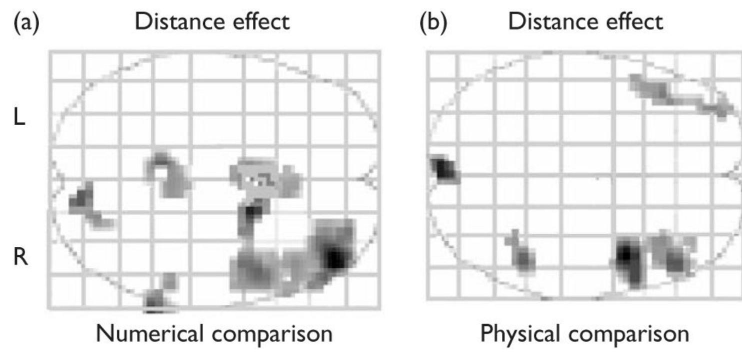

Fig. 1.
Areas more active for neutral close versus neutral far distances(distance 1>distance 4). (a)Numerical comparison task; (b) physical comparison task (*P*<0.05 corrected; rendered on a glass brain).

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Table 1

Behavioural results for the two tasks

	Close distance (ms) (SD) [%E]	Far distance (ms) (SD) [%E]
Numerical comparison		
Neutral	834 (104.00) [7.6]	715 (57.90) [5.6]
Incongruent	852 (104.92) [11.8]	754 (126.36) [9.0]
Physical comparison		
Neutral	696 (56.93) [2.5]	651 (47.17) [0.0]
Incongruent	835 (78.82) [9.2]	670 (73.04) [5.0]

Physical comparison (*n*=10) and numerical comparison (*n*=12): mean reaction times in milliseconds (ms); standard deviations (SD; in parenthesis) and error rates [%E].

Table 2

Fixed effects analysis of baseline contrasts (numerical/physical comparison>fixation), distance effects (neutral close distance>neutral far distance) and congruity effects (maximal interference>minimal interference)

Side	Numerical comparison	*x*	*y*	*z*	*k*	*Z*	*P*	Side	Physical comparison	*x*	*y*	*z*	*k*	*Z*	*P*
Baseline contrasts								**Baseline contrasts**							
L	S/MFG	−8	7	55	2036	Inf	0.000	B	MFG	−8	3	59	1732	Inf	0.000
R	MFG	8	6	51		Inf	0.000		Ext. to CingG	0	−26	23		Inf	
L	Ext.to precuneus	−28	−59	58		Inf	0.000		Ext. to CingG	20	−42	24		7.78	
R	ACC	4	13	25	14	5.75	0.001	L	MFG, ext. to SFG	−44	40	27	53[a]	6.77	0.000
R	MFG	44	54	−3	2	5.13	0.037	R	Ext. to precentral gyrus	40	−20	67	8	5.69	0.003
L	CingG, STG	−20	−42	24	30[a]	5.56	0.000	R	Ext. to MFG	40	15	58	7	5.12	0.004
R	STG	67	−19	1	2	4.50	0.037	L	Precentral gyrus	−32	−24	60	4	4.96	0.014
R	IPL (ext. to IPS and post.CingG)	40	−44	54	510[a]	Inf	0.000	R	IPL (ext. to IPS), SMG	40	−48	58	244[a]	Inf	0.000
L	Ext. toANGand SMG	−59	−60	40	13[a]	4.87	0.001	L	IPL (ext. to IPS)	−55	−44	57	65[a]	6.89	0.000
L	IPL	−51	−26	23	8[a]	5.38	0.004	L	SPL	−28	−55	58	8	5.32	0.003
B	Le post.CER, le lingual g., ri ant.CER	0	−67	−11	44[a]	6.24	0.000	R	Ant.CER	4	−66	−8	25	5.55	0.000
R	Ant.CER	24	−55	−16	13[a]	5.54	0.001	L	Post.CER	−36	−59	−23	7	5.11	0.004
L	Post.CER	−36	−59	−23	7	5.27	0.005	R	Ant.CER	36	−59	−23	4	5.06	0.014
								L	Ext. to thalamus	0	−4	8	4	5.25	0.014
Distance effect								**Distance effect**							
R	MFG, IFG (incl.DLPC), ext. to SFG	44	48	20	216[a]	6.61	0.000	R	MFG (incl.DLPC), ext. to IFG	44	9	25	95[a]	5.04	0.010
L	Ext. toMFG, SFG, ACC	0	14	47	81[a]	4.28	0.033								
Congruity effect								**Congruity effect**							
	NS							L	MFG, IFG (ext. to DLPC)	−36	50	−3	74[a]	4.52	0.034
								L	MOG, IOG, lingual gyrus	−28	−62	3	77[a]	4.64	0.028
								L	Post.CER (declive)	−12	−74	−11	95[a]	4.59	0.010

ACC, anterior cingulate cortex; ANG, angular gyrus; CER, cerebellum; CingG, cingulate gyrus; DLPC, dorsolateral prefrontal gyrus; I/M/SFG, inferior/middle/superior frontal gyrus; I/M/STG, inferior/medial/superior temporal gyrus; I/M/SPG, inferior/medial/superior parietal gyrus; I/M/SOG, inferior/medial/superior occipital gyrus; IPS, intraparietal sulcus; SMG, supramarginal gyrus; SPL, superior parietal lobe; ext., extending; ant., anterior; post., posterior; NS, nonsignificant.

Coordinates transformed to Talairach & Tournoux space [16].

Note: *k*=cluster size in voxel; *Z*=*Z*-value; *P*=corrected *P* on cluster level.

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[a] Localmaximumof a bigger cluster.